

# BEAM-BEAM EFFECTS IN BEPCII

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## Abstract

We first introduce the design parameters of the Beijing Electron-Positron Collider II (BEPCL) and the simulation study of beam-beam effects during the design process of the machine. The main advances since 2007 are briefly introduced and reviewed. The longitudinal feedback system was installed to suppress the coupled bunch instability in January 2010. The horizontal tune decreased from 6.53 to 6.508 during the course of data taken in December, 2010. The saturation of the beam-beam parameter was found in 2011, and the vacuum chambers and magnets near the north crossing point were moved 15 cm in order to mitigate the long range beam-beam interaction. At the beginning of 2013, the beam-beam parameter achieved 0.04 with the new lower  $\alpha_p$  lattice and the peak luminosity achieved  $7 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ .

## INTRODUCTION

The Beijing Electron-Positron Collider (BEPCL) was constructed for both high energy physics and Synchrotron Radiation (SR) research. As a unique  $e^+e^-$  collider operating in the  $\tau$ -charm region and the first SR source in China, the machine has been operated for well over 16 years since it was put into operation in 1989.

BEPCLII is an upgrade project from BEPCL. It is a double ring machine. Following the success of KEKB, the crossing scheme was adopted in BEPCLII, where two beams collide with a horizontal crossing angle of  $2 \times 11 \text{ mrad}$ . The design luminosity of BEPCLII is  $1.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  at 1.89 GeV, which is about 100 times higher than BEPCL [1]. The main design collision parameters are shown in Table 1. In March 2013, the peak luminosity achieved

Table 1: Design Parameters of BEPCLII.

E	1.89 GeV	$\nu_s$	0.034
I	910 mA	$\alpha_p$	0.024
$I_b$	9.8 mA	$\sigma_{z0}$	0.0135 m
$n_b$	93	$\sigma_z$	0.015 m
$V_{rf}$	1.5 MV	$\epsilon_x$	144 nmrad
$\beta_x^*/\beta_y^*$	1.0/0.015 m	Coupling	1.5%
$\nu_x/\nu_y$	6.53/5.58	$\xi_y$	0.04
$\theta_c$	22 mrad	$\tau_x/\tau_y/\tau_z$	3.0e4/3.0e4/1.5e4

$7.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  with 120 bunches and beam current 730 mA, where a lower  $\alpha_p$  lattice was used.

In the following, we first introduce the simulation study of the beam-beam interaction during the design course of the machine. Then we review the performance and optimization of the real machine.

## SIMULATION STUDY DURING DESIGN

### Code Development

We have developed new parallel strong-strong beam-beam code, which is used to study the effects in BEPCLII [2]. The main characteristics of the code are listed below.

- Particle-in-cell. The Triangular Shaped Cloud (TSC) method is employed for the charge assignment, where the charge of each macroparticle is assigned to its nine nearest points by weight.
- Synchrotron motion is included. The transportation through the arc is same as that of Hirata's BBC code [3].
- The beam-beam potential is calculated by solving the Poisson equation with open boundary.
- Bunch length effect is included by longitudinal slices and the interpolation of beam-beam potential is done when the collision between two slices is considered, which helps to reduce the required slice number.
- It is assumed that a particle in one slice will not jump into non-adjacent ones on the next turn. It seems that this assumption has been valid so far, especially in the ordinary collision scheme (where the required slice number is only about 5).
- Lorentz boost is used to consider the crossing angle effect [4].

### Code Check

- The geometrical factor of luminosity reduction for head-on collision. The loss in luminosity due to geometrical effect for nominal BEPCLII parameters is 86%, and the code tracking result agrees well.
- The geometrical factor of luminosity reduction for collision with finite crossing angle. The loss in luminosity due to geometrical effect for design BEPCLII parameters is 80%, and the code tracking result agrees well.
- The beam-beam field calculated by the code for the Gaussian beam distribution agrees well with the Bassetti-Erskine formula.
- The synchro-betatron mode agrees well with that predicted by the hollow beam matrix model [5].
- The luminosity result for BEPCLII agrees well with that of K. Ohmi's code [6].

## Simulation Result

The achieved beam–beam parameter  $\xi$  with collision is defined as

$$\xi_u = \frac{Nr_e}{2\pi\gamma} \frac{\beta_u^0}{\sigma_u(\sigma_x + \sigma_y)} \quad (1)$$

where  $\beta^0$  is the nominal beta function without collision, and  $\sigma$  is the disturbed beam size with collision. If we don't consider the finite bunch length and finite crossing angle, the bunch luminosity can be represented as

$$L = \frac{N^2 f_0}{4\pi\sigma_x\sigma_y} \quad (2)$$

where  $\sigma$  is the disturbed beam size with collision. In the normal case,  $\sigma_y \ll \sigma_x$ , the achieved  $\xi_y$  can be represented by luminosity,

$$\xi_y = \frac{2r_e\beta_y^0}{N\gamma} \frac{L}{f_0}. \quad (3)$$

With the design parameters, the maximum  $\xi_y$  only achieves 0.025, which is shown in Fig. 1. This is bad news for the BEPCII team, since  $\xi_y$  needs to achieve 0.04 if we want to achieve the designed luminosity with the designed beam current. We therefore did some estimation to determine if it would be feasible to inject more bunches, and it seems that this would be possible.

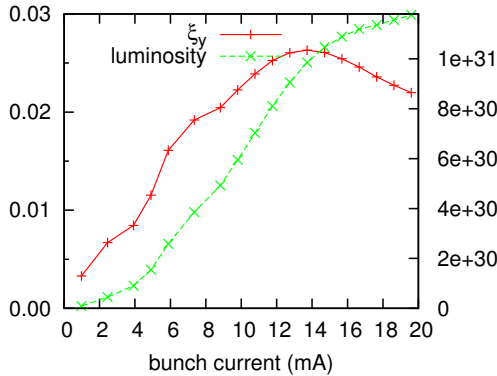


Figure 1: The achieved  $\xi_y$  and bunch luminosity versus bunch current with design parameters.

The beam–beam performance is very sensitive to the working point. The normalized luminosity versus tune is depicted in Fig. 2. The best working point is near (0.505, 0.570), where the luminosity is about 80% of the design value. That is to say, we could achieve  $8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  with the designed bunch current, bunch number and optimized working point.

The full horizontal crossing angle between colliding beams is 22 mrad. The luminosity reduction factor is less than 10% at (0.53, 0.58), however it is about 30% at (0.51, 0.57). It seems that the luminosity loss due to a finite crossing angle is more serious the closer the horizontal tune is to 0.5, the high luminosity working point region.

We also tried to analyze the coupling contribution and carried out some simulations at different working points.

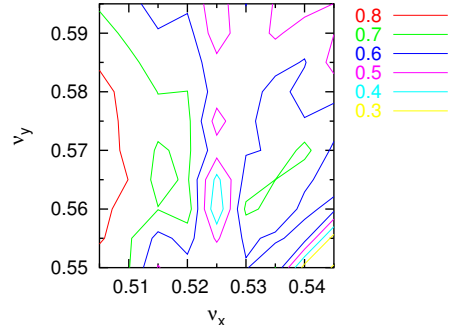


Figure 2: Tune survey of luminosity. The luminosity is normalized to the design value.

Table 2: Coupling contribution at different working point.

Tune	Coupling	Max $\xi_y$	Lum
(0.510, 0.575)	0.5%	0.041@11 mA	12.3e30
	1.0%	0.037@12 mA	12.1e30
	1.5%	0.034@13 mA	12.1e30
(0.530, 0.580)	0.5%	0.026@7 mA	5.0e30
	1.5%	0.026@13 mA	9.2e30
(0.535, 0.575)	0.5%	0.031@9 mA	7.6e30
	1.0%	0.027@9 mA	6.6e30
	1.5%	0.023@9 mA	5.6e30
(0.540, 0.590)	0.5%	0.025@11 mA	7.6e30
	1.0%	0.024@11 mA	7.2e30

The results are summarized in Table 2. It seems that we have to move the horizontal tune closer to 0.5 and ensure that the emittance coupling is less than 0.5% if  $\xi_y$  is expected to achieve 0.04.

## PERFORMANCE AND OPTIMIZATION

The first electron beam was stored in the SR ring in November 2006. Optics measurement and correction was studied at that time. The backup collision mode was first tuned in the spring of 2007, during the course of which we learned the collision tuning. The superconducting final focus magnet was installed in the summer of 2007. The detector was installed in June 2008, and this completed the construction of the machine. Here, we review the machine tuning history in chronological order.

### Phase I: Autumn of 2008 to Summer of 2010

The big events in this period are listed below.

- January 2009. Profile monitor, which caused very strong longitudinal multibunch instability, was removed from the positron ring.
- May 2009. Horizontal tune was moved to 0.51 from 0.53. Luminosity reached  $3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ , which is the 'design goal' of the government funding agency.
- January 2010. Longitudinal feedback system was installed and began to work.



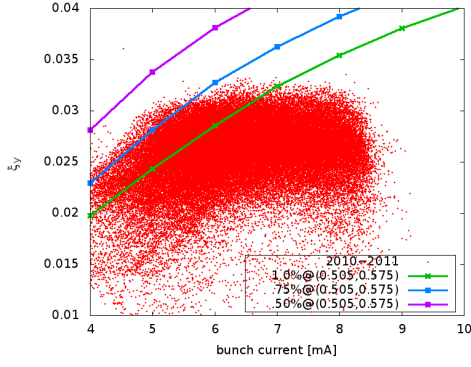


Figure 7: Achieved beam–beam parameter in 2010–2011. The lines show the simulation result with different coupling.

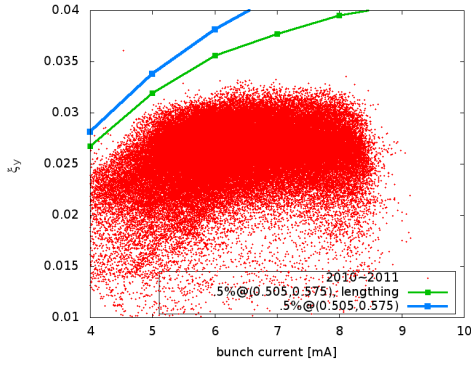


Figure 8: Beam–beam loss due to bunch lengthening, which does not explain the beam–beam parameter saturation in real machine.

the maximum beam–beam parameter is still above 0.04.

The nonlinear arc may also reduce the luminosity performance. We use Hirata’s BBC [3] code as a pass method in Accelerator Toolbox (AT) [7] to simulate the weak–strong beam–beam interaction. The map in the arc is implemented using the element-by-element symplectic tracking in AT. Figure 9 shows the comparison between the ideal transfer matrix map and element-by-element tracking in arc. The lattice really reduces the beam–beam performance, but we did not believe that the saturation was mainly caused by the crosstalk between nonlinear arc and beam–beam force. On the other hand, we could not ignore the simulation result, which told us that we should put more emphasis on the sextupole optimization.

There is another crossing point (NCP) in the north of the two rings, where the colliding beams are separated vertically by about 8 mm and the full horizontal angle is about  $2 \times 0.15$  rad ( $17.7^\circ$ ). We still use the weak–strong code (AT and BBC) to study the parasitic beam–beam effect, which is shown in Fig. 10. The achieved  $\xi_y$  is only about 0.035 with 8 mm separation at NCP

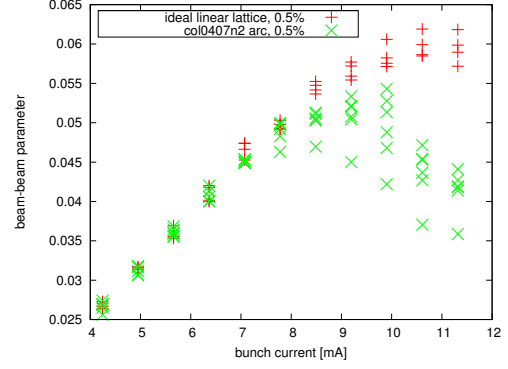


Figure 9: The luminosity loss due to the realistic arc. The arc map is implemented using element-by-element tracking. The ideal linear lattice means the map is represented by a transfer matrix.

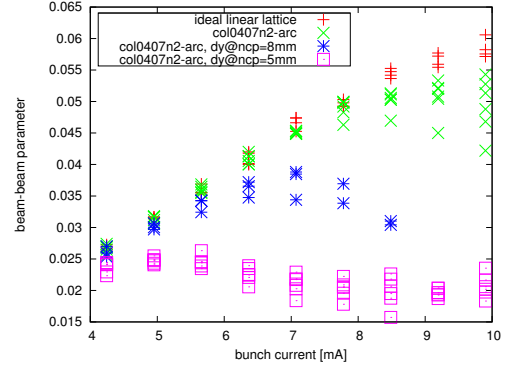


Figure 10: The luminosity loss due to nonlinear arc and long range beam–beam interaction at NCP.

### Phase III: Autumn of 2011 to Summer of 2012

The big events in this period are listed below.

- In the summer shutdown of 2011, the NCP chambers and magnets were moved 15 cm, 1/4 of the rf bucket. The horizontal separation between colliding bunches is greater than  $30\sigma_x$ .

After the hardware modification, the beam–beam performance did not increase as expected, which is shown in Fig. 11. This could be explained to some extent by the large longitudinal offset of the collision point. In 2011–2012 commissioning year, the offset is about 3 mm, and it is about 6 mm in February 2012. We did not put enough emphasis on monitoring the parameter during collision at that time.

### Phase IV: Autumn of 2012 to March 2013

The big events in this period are listed below.

- Lower  $\alpha_p$  mode was first tested at 2.18 GeV in February 2013. The  $\xi_y$  record 0.033 was broken after about two years.
- One bunch every three buckets, and even one bunch every two buckets, injection was tested in the machine

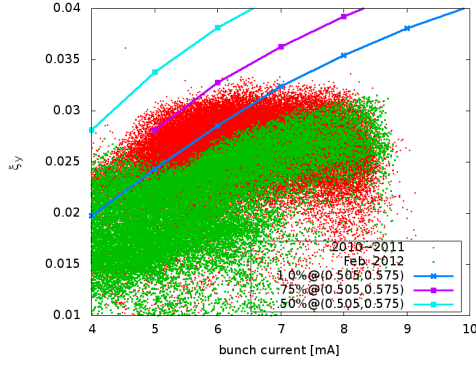


Figure 11: Beam-beam parameter achieved in 2011 and 2012. The mitigation of long range beam-beam interaction at NCP did not bring any improvements.

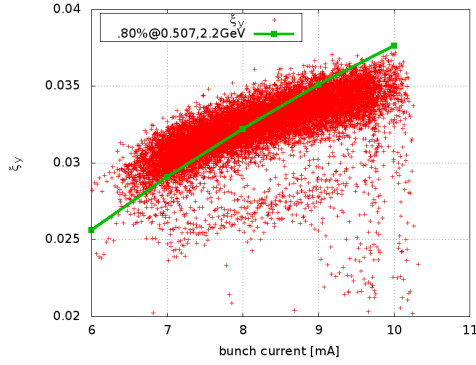


Figure 12: Achieved beam-beam parameter at 2.18 GeV with new lattice in 2013.

study of March 2013. The peak luminosity achieved  $7.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  at 1.89 GeV.

The momentum compaction factor of the new lattice is about 0.017, and the old one is 0.024. The reduction of  $\alpha_p$  is achieved by increasing the horizontal tune from 6.5 to 7.5. During the lattice design, we also optimized the chromatic distortion and some nonlinear resonance driving terms. However we still did not establish a so-called ‘standard’ that could tell us if the lattice is good enough.

The achieved beam-beam performance at 2.18 GeV is shown in Fig. 12. We also did some machine study in order to increase the peak luminosity at 1.89 GeV. The achieved beam-beam parameter with different bunch pattern is shown in Fig. 13. The maximum  $\xi_y$  is above 0.04. It seems that the multibunch effect reduces the beam-beam performance, which would be a serious limitation if we were to continue to increase the luminosity.

## SUMMARY

We review the collision optimization history of BEPCII. The suppression of multibunch longitudinal instability and moving the horizontal tune close to 0.5 helped us to increase the luminosity. The mitigation of long range beam-beam interaction seems not so effective as expected, indi-

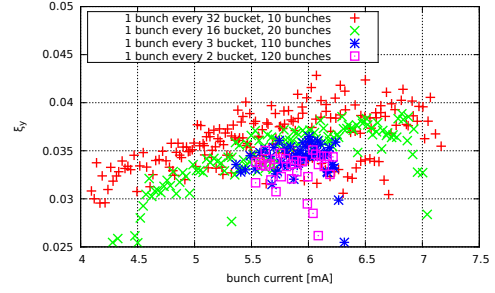


Figure 13: Achieved beam-beam parameter at 1.89 GeV with different bunch pattern in 2013.

cating that maybe the real vertical separation is greater than estimated. The lower  $\alpha_p$  lattice helped us to achieve the  $\xi_y$  record of 0.04 at 1.89 GeV.

The simulation study is very important both in the design and the daily commissioning. It gives a benchmark in normal operation and lets us know if the status is optimized enough, even though we could approach the simulation result and never go beyond it. The difference between the simulation and the optimized result is about 10–20%. It should also be emphasized that we would like to use the maximum achieved  $\xi_y$  in the simulation as the beam-beam limit in the simulation.

Increasing beam current is a must to increasing the luminosity. However, it seems the multibunch effect is very serious. The study to cure the instability and even find the instability source will be very important in the future. In the near future, we’ll test a new lattice with  $\alpha_p$  about 0.017, larger emittance (100 nm→130 nm) and lower  $\beta_y$  (1.5 cm→1.35 cm). The colliding bunch current could be higher with the new mode and the beam current could be higher with same bunch number. It is expected that this could help us to increase the luminosity.

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